

PROJECT ADMINISTRATION DATA SHEET

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Project No. E-21-675 GTRI/ST DATE 1 / 6 / 84

Project Director: Dr. R. P. Webb School/Lab Electrical Engineering

Sponsor: Lockheed-Georgia Company, Marietta, GA

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Estimated: \$	<u>25,000</u>	\$ <u>25,000</u>
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Title: Engineering Analysis and Design of Aircraft Power Systems

ADMINISTRATIVE DATA

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Defense Priority Rating: None Military Security Classification: None
(or) Company/Industrial Proprietary: None

RESTRICTIONS

See Attached --- Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of \$500 or 125% of approved proposal budget category.

Equipment: Title vests with None proposed.

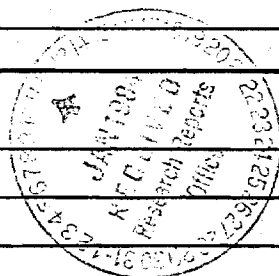
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SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 8/1/84

Project No. E-21-675

School/Lab EE

Includes Subproject No.(s) _____

Project Director(s) R.P. Webb

GTRI / GIT

Sponsor Lockheed-Georgia Company, Marietta, GA

Title Engineering Analysis and Design of Aircraft Power Systems

Effective Completion Date: 12/31/83

(Performance) 12/31/83

(Reports)

Grant/Contract Closeout Actions Remaining:

☐

None

☒

Final Invoice or Final Fiscal Report

☐

Closing Documents

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Final Report of Inventions

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Govt. Property Inventory & Related Certificate

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WORK STATEMENT:

**DEVELOPMENT OF PROCEDURES FOR DESIGN AND PERFORMANCE
EVALUATION OF CARGO AIRCRAFT ELECTRIC POWER SYSTEMS**

for:

LOCKHEED GEORGIA COMPANY

by:

**ELECTRIC POWER LABORATORY
SCHOOL OF ELECTRICAL ENGINEERING
GEORGIA TECH**

participating faculty:

A. S. Debs _____

H. B. Püttgen _____

R. P. Webb _____

Objectives

The objective of the proposed effort is to develop methodologies for design and performance assessment of alternative aircraft electric power supply and distribution systems. Cargo type aircraft provide the specific focus.

Deliverable Items

The items to be delivered are:

A computer program encompassing appropriate models for complete aircraft power system representation and specific procedures for performance and reliability assessment of alternative given system configurations.

A report defining program development, operation and utilization.

Complete program documentation

Effort

A preliminary investigation has indicated that many of the sophisticated techniques utilized in the electric power utility industry can be adapted and augmented to provide systematic procedures for design and analysis of aircraft electric power systems. Further, increasing electrification and electrical complexity of aircraft makes the electric power system increasingly critical to the aircraft function. Reliability of the system, maintenance of function under contingent conditions by appropriate controls, becomes a crucial issue to overall aircraft system operation. Improved procedures for electric power system design and evaluation are clearly required and are addressed in this proposed effort.

The proposed effort is in three phases:

Phase I. Development of appropriate load and subsystem models.

Phase II. Development and implementation of system design and analysis procedures.

Phase III. Program testing and evaluation.

In Phase I, models of alternative technologies for power generation, distribution and control will be developed. The models will be appropriate for computer implementation in modular form so that alternative sub-system technologies can be evaluated in the context of the systems analysis procedures.

Phase II relates to development of specific procedures for performance and reliability assessment of the electric power system for various alternative sub-systems and loads. Power flow, voltage profile, short circuit currents, and distribution control calculations will be incorporated. Procedures for system reliability assessment and sensibility analysis will be implemented.

The testing embodied in Phase III is for the purpose of evaluating the program. Specifically it is proposed to utilize the program to perform a detailed study of the aircraft distribution system with regard to voltage level and frequency. For a given aircraft configuration the effects of a-c, d-c, or a-c/d-c distribution at specific feasible voltage levels on electric power system performances, reliability and weight will be assessed.

Proposed project duration is one calendar year from initiation.

The following specific tasks and associated effort levels are defined:

Task	Description	Effort Level
1	Model Development	4 faculty man-months
	a. Generation Systems	5 graduate assistant man-months.
	Variable Speed Drives	
	Constant Speed Drives	
	D-C Link	
	Cyclo-converters	
	b. Distribution and Control	
	A-C systems	
	D-C systems	
	A-C/D-C systems	
	Transformers and power supplies	
	Cable models	
	Displays and controls	
	c. Loads	
	Control Actuation	
	Environmental systems	
	Avionics	
2	Analysis Program Development	4 faculty man-months
	a. Performance Analysis Modules	5 graduate assistant man months
	Power flow	
	Voltage profile	
	Fault current	
	b. Operational Simulation	
	Normal Operation	
	Contingent operation	
	Load management	
	c. Reliability Analysis	
	Subsystem reliability	
	Sensitivity analysis	
	Composite reliability	
3	Testing and Evaluation	1 faculty man-month
	a. Test configuration definition	2 graduate assistant man months
	b. Data collection	
	c. Performance and reliability analysis	
4	Documentation	1 faculty man-month
	a. Project report	
	b. Computer program documentation	

Budget

10	faculty man-months	@ \$8,600	\$ 84,600
12	graduate assistant man-months	@ \$3,000	36,000

TOTAL PROJECT COST

\$ 122,000

REPORT
ON
PRELIMINARY INVESTIGATION
OF
CARGO AIRCRAFT ELECTRIC
POWER SYSTEMS

by
Electric Power Laboratory
School of Electrical Engineering
Georgia Institute of Technology

Participating faculty:

A.S. Debs _____
H.B. Puttgen _____
R.P. Webb _____

1. SUMMARY

This report summarizes a study of electric power supply for future cargo-class aircraft. The objective of the study was to define methodologies to aid in the design and evaluation of increasingly complex and critical aircraft electrical systems. Embodied in this objective is an assessment of developing applicable technologies, definition of appropriate models to evaluate these technologies in the aircraft electric supply and distribution system context, and definition of objectives, methodologies and structure of required system analysis and design procedures.

A main conclusion of the study is that a definite need exists for the development of appropriate analytical procedures applicable to aircraft electric power system evaluation and design. Many of the required procedures can be adapted from the many advanced procedures employed in the conventional electric utility industry. However, the more critical aspect of system reliability and the specific nature of the electric loads dictates that existing methods be considerably tailored, and that some new techniques be incorporated.

The analysis procedure defined in this study contains three major aspects:

- (1) A procedure for analysis of system reliability which can evaluate the reliability of supply to every load and relate this to functional system reliability.
- (2) An operational performance analysis procedure to evaluate the quality and availability of power under both normal and contingent operation and aid in development of appropriate system structures and controls to maintain functional operation in contingent

conditions.

- (3) A Sensitivity analysis procedure which will enable trade-off studies of alternative systems with respect to operation and reliability.

The key areas that must be addressed in terms of developing technology and modeling include:

- (a) Power distribution including voltage levels and frequency, distribution bus structure, transformers and individual load power supply, cable technology, and system protection.
- (b) Generation systems with regard to new generator designs and generation control.
- (c) Load models including control actuators, environmental systems, avionics and other specialized loads.

2. INTRODUCTION

In November 1983, the Electric Power Laboratory of the School of Electrical Engineering at Georgia Tech contracted with the Lockheed-Georgia Co. to study aircraft electric power systems relative to future cargo aircraft. The study, which was conducted during the period January-March 1984 is summarized in this report.

Initially, the parameters of the study to be conducted were not well defined. However, preliminary investigation readily provided objectives and structure. Specifically, it became clear that rapid change is taking place in aircraft electrical loads; electric actuators, electrical environmental systems, avionics, discrete digital controls, etc. Future aircraft designs will certainly be increasingly electrified. Indeed, serious consideration is being given to the so-called all-electric-aircraft whereby functions which have been historically performed by hydraulics and pneumatics are operated electrically. Various studies have been done on the impact of electrification end items (loads). However, the many issues and opportunities associated with electric power supply and delivery for increasingly electrified aircraft have not been similarly addressed. As aircraft operations become increasingly dependent on the electric power system, the operation and reliability of this system becomes crucial. Failure modes must be clearly defined and the system so structured as to admit continued safe operation under various contingencies and sub-system failures. With different load power requirements, and distribution of the load about the aircraft, the manner of distribution of electric power (d-c, a-c, hybrid, voltage levels), as well as control of the power flow, impacts not only operation of the aircraft but also aircraft design itself in terms of weight and cost.

Methodologies to address these key issues in aircraft electric power supply are clearly required. The Georgia Tech study focused on defining key issues and analysis procedures. Specifically the objectives of the study were defined as:

- (1) Assessment of key issues in future aircraft power supply systems and defining modeling efforts required to adequately represent these in total system evaluation.
- (2) Definition of appropriate procedures for electric power system analysis and evaluation.

Since the all-electric-aircraft represents the extreme in aircraft electrification, the study was oriented to encompass that configuration. That is, consideration was given to procedures whereby trade-off studies for a variety of configurations and technologies can be accommodated.

Chapter three of this report addresses the technological issues and modeling requirements. Chapter four defines appropriate procedures for system analysis and evaluation.

3. TECHNOLOGICAL ISSUES FOR THE ALL-ELECTRIC AIRCRAFT

3.1 Introduction

The All-Electric Aircraft (AEA), which represents the extreme case for aircraft electrification, is not an entirely new idea as it has been studied and partially applied to modern fighter/attack aircraft such as the F16, the F18 and the Mirage 2000. These aircraft make extensive use of electrical transmission of information using "Fly by Wire" and "Fly by Light" technologies and they also use some electrical actuation. However, comprehensive distribution system analyses for an AEA in the large cargo or large passenger class are few and incomplete. The purpose of this chapter is to provide an overview of the available technologies to be used for large cargo AEA and also to identify some issues which must still be studied in greater detail to achieve a comprehensive grasp of all problems relating to the bulk distribution of electric power in the AEA. The chapter addresses the following problems:

- Power Distribution
- Generator Systems
- Actuator Systems
- Miscellaneous topics such as load modeling, cable technology and transformer technology.

It should be noted that the so-called All-Electric Aircraft is the extreme application of the electrification of an aircraft. Indeed, one should also analyze various hybrid configurations where all or some hydraulic actuation systems are maintained either as primary or secondary systems. Such hybrid systems are perfectly feasible and their relative merits, compared to

the A E A solution, should be evaluated in terms of overall aircraft performance, system reliability, weight and cost.

3.2 Power Distribution

A key issue to be considered when investigating the feasibility of an All Electric Aircraft (AEA) is what kind of power distribution scheme should be used. The problem of electric power distribution is not entirely new with the AEA concept but its importance has very clearly grown when considering a cargo AEA; this is so for two major reasons:

- The power levels involved are very much higher when compared with an aircraft still using hydraulic actuators;
- The physical distances over which non-negligible amounts of electrical energy are to be distributed are such that voltage drops and heat losses have to be taken into account. Indeed, the cable length between an outer engine-generator and the tail control surfaces can reach several hundred feet for large cargo aircrafts.

For the purpose of study it should be assumed that the aircraft will use no bleed air at all, not even for environmental control systems. This assumption means that all loads on board will be supplied electrically thereby yielding the most stringent design requirements on the electrical distribution system.

As will be discussed in paragraph 3.3, the on-board generators can be designed to supply two forms of electrical energy:

- three phase ac, 115/200 V, 400 Hz
- 270 V dc.

Therefore, three fundamental types of distribution systems are possible:

- all three phase ac
- all dc
- hybrid system.

The selection of the design solution will heavily depend on the types of loads to be serviced on-board. Four types of loads can be distinguished follows:.

- A. Aircraft avionics and instruments. These loads are already existing in present day technology which means that the degrees of freedom on the distribution system are restricted to satisfy the power supply requirements of these existing loads. In most cases these loads are supplied with either 270 V dc or with 28 V dc.

In order to increase the flexibility of the distribution system design, a study must be done to determine not only what the current requirements are for existing avionics and flight instrumentation, but also to determine what type of supply systems they could use while still performing the tasks they were originally designed for. A key issue here is that if some alternate forms of energy supply systems are feasible for existing avionics and instrumentation, then it may very well be feasible to redeploy and relocate a significant number of power transformers away from the individual loads.

- B. Aircraft flying control surfaces actuation and controls. This is an entirely new category of electrical loads which can be supplied either from an ac source or a dc source. Actuators are discussed in greater detail in paragraph 3.4.
- C. Aircraft landing gear deployment and retraction. This is also an entirely new category of electrical loads which can be supplied either from an ac source or a dc source.
- D. Environmental Control Systems (ECS). This type of load has traditionally

relied partially on bleed air extraction from the aircraft's engines. Therefore, from an electrical system's point of view, this should be regarded as a new type of load. ECS can be supplied either from an ac source or from a dc source. However, the ECS offers a third and interesting alternative: this type of load could potentially be supplied using an only partially controlled ac source where only the ratio of voltage magnitude to frequency is constant. This offers an interesting possibility of supplying the ECS while bypassing portions of the electric generator power conditioning circuits.

A study should be carried out to carefully analyze the effects of partially supplying the environmental control systems from a variable voltage-variable frequency source directly from the engine-generator armature windings.

A final category of load could be viewed as the electrical engine starter. However, this is only a reverse mode operation of the on-board generators. The aircraft engine starting mode merely contributes to the design process of the generator-cycloconverter ensemble and should not be considered as an electrical load under flight conditions.

3.2.1 Some Potential Distribution System Schemes

As mentioned earlier, an all ac distribution system, or an all dc system or, finally, a hybrid system can be considered possible. In all three cases consideration must be given to the bus structure retained. The present day technology has all on-board generation feeding one or two common buses to which all electric loads are directly connected. The common bus can either be an ac bus or a dc bus. The key point is that the entire distribution system structure is radial, no meshes are included. This means that no redundancy is

built into the system by use of network meshes; all redundancy is obtained by straight duplication of individual components.

It appears that potential weight savings and/or reliability performance increases can be achieved if the entire AEA is viewed as a power system where a meshed network structure would be designed to achieve overall and prescribed loss of load probability indices as well as individual load center power supply availability indices.

This meshed structure philosophy is very different from a strictly radial structure in that the particular power flows over each cable section are not only directed by individual load centers but also by overall system topology. A meshed network structure can greatly enhance the potential impact of astute load rescheduling and load shedding schemes.

The ac distribution scheme offers the potential advantage of providing for bulk power transmission at high voltages (using step-up and step-down transformers) thereby yielding reduced weights of the required cables. The clear disadvantages may well be the requirement for additional transformers. The weight issue of transformers will be further discussed in paragraph 5.3.3.

The dc distribution scheme can only be envisioned at the 270 V dc as short circuit currents would be prohibitive should a 28 V dc level be selected for the bulk distribution of power. Using the 270 V dc for transmission has the major attractive advantage of having directly available a power source which can be used, without further conditioning, by many aircraft loads thereby bringing significant weight savings in required transformers. The clear disadvantage of an all dc distribution system for the AEA are twofold: rather high short circuits currents, which are of the dc type thereby requiring more complex breaker circuits, and, also the requirement to use rather large distribution cables for the bulk transmission as high voltage

distribution cannot be readily achieved using dc without using complex and heavy rectifier inverter subsystems.

Although 270V dc is a natural voltage level when primary energy source is rated 115/200V ac and 400 Hz, it may well be feasible and advantageous to use an alternate dc voltage level for electric power distribution. Such an alternative should be investigated to determine its feasibility and if so at what particular voltage level it should be implemented.

In view of the potential benefits and disadvantages of both the ac and dc distribution schemes, it appears that detailed studies should be undertaken for each potential type of AEA to examine which hybrid type of distribution would bring the best overall compromise. In this evaluation process the weight factor would have to be a dominant factor once all other performance indices are met.

Finally, the overall power distribution scheme retained is likely to be influenced by the particular engine location on the AEA.

Electric power distribution schemes for the AEA should be investigated for the following types of engine configurations:

- four engines, two on each wing;*
- two engines, one on each wing;*
- three engines, one on each wing, one in the tail;*
- three engines, all three in the tail;*
- two engines, all in the tail.*

3.3 Generator Systems

3.3.1 Basic Issues

Future generator arrangements for cargo aircraft will use one of two

basic configurations:

- Variable speed drives
- Constant speed drives.

In both cases the accepted practice has two generators mounted on each aircraft engine shaft. This means that an eight generator configuration is proposed for a four engine aircraft, six generators for three engines and four generators for a two engine aircraft. This technique is proposed in view of its inherent reliability advantage when compared to the one generator per engine philosophy. However, for an all electric aircraft a crucial issue becomes the required installed capacity for each generator for a given demand level depending on the number of generators. In addition to the obvious flight reliability issues always present with multiengine aircrafts, one must now take into account the electrical load supply reliability as well.

Accurate reliability models must be developed not only for the electrical generators themselves and for their control systems, but also for the engines themselves. Such reliability models are certainly already available; however, they most probably need to be adapted to the needs of an electrical load supply reliability study. A key point here will be the adequate modeling of common mode failures such as represented by total or partial engine failures.

The variable speed configuration has the generator rotor shaft directly connected to the engine's shaft. This configuration is very attractive in that substantial space savings are feasible in the design of the engine's nacelle. This space savings feature will result in smaller nacelles having less drag which will be significant for aircrafts operating in the mach 0.9 to 1.2 range. The major disadvantage of the variable speed configuration is the need for some additional regulation system to achieve a constant frequency and constant voltage supply. The variable speed generator configuration will be

discussed in greater detail in paragraph 3.3.2.

The constant speed drive configuration is more traditional in that it uses a speed converter and a gear box to provide the generator's rotor shaft with a constant rotational speed, regardless of the engine's actual speed. The obvious advantage of this configuration is the fact that no external regulation systems are required to achieve a constant frequency supply system. However, the speed converter and gear box do occupy additional space in the engine nacelle and, therefore, will require a nacelle design with higher drag when compared with the variable speed configuration. The constant speed generator configuration will be discussed in greater detail in paragraph 3.3.3.

It seems that additional work is required to evaluate the additional cost, over the aircraft lifetime, due to increased nacelle drag inherent with the constant speed generator technology.

A key concern in generator design for aircraft application is size and/or weight. In order to achieve acceptable size and weight, the generator design must incorporate a very highly efficient and robust field source and armature windings. All proposed generator designs are of the ac type where the armature windings are on the stator (3, 6, 9 or even higher number of phases) and where the field source is located on the rotor. For all aircraft applications the nominal frequency selected is 400 Hz which appears to be a solidly entrenched standard. Higher frequencies than 60/50 Hz are of course desirable as higher frequencies reduce the size of the devices for the same installed capacity. The rotors considered are of two fundamental types:

- Solid rotors
- Wound rotors.

3.3.1.1. Solid Rotors

Solid rotor generators, generally referred to as Permanent Magnet Generators (PMG), became feasible as the Samarium Cobalt (SmCo) magnets became available at an industrial level. These magnets have an energy product of 20 to 30×10^6 Gauss-Oersted, with projected levels of 50×10^6 Gauss-Oersted. The greatest difficulty associated with these materials is their relatively poor mechanical strength properties. However, recent mechanical design progress has made it possible to use Samarium Cobalt permanent magnet rotors.

Several types of solid rotor machines can be used as follows:

- Homopolar inductor machine;
- Lundell synchronous machine;
- Asynchronous induction machine;
- Permanent magnet synchronous type machine.

By far the most commonly referred to design is the synchronous type generator where the rotor has a salient pole design made of Samarium Cobalt material.

A significant advantage for the permanent magnet generator of the synchronous type is the fact that it can very readily be used as a motor for the start-up procedure of the engines. This is feasible as the field is always present irregardless of the rotational speed, which is not true for a rotating rectifier type of machine.

A major disadvantage of the permanent magnet generator is inherent to the fact that the rotor bound flux cannot be easily shut off. This is potentially very dangerous in the case of armature winding short circuits. The only way to then suppress the rotor bound flux is to physically disconnect the rotor shaft from the engine's shaft; which is not convenient in most cases. This disadvantage of the PMG design explains why the wound rotor design is still being pursued.

Major development of the PMG designs have been achieved by the General Electric Company.

3.3.1.2 Wound Rotors

The wound rotor design uses a more classical approach to the synchronous machine design where the rotor is made up of 4 to 8 salient poles each carrying a wound field winding. In order to achieve proper size reductions, the rotor is cooled down to only a few degrees Kelvin to achieve close to a superconducting state. Major design work has been carried out by the Westinghouse Electric Corporation where Helium is used as the coolant for the rotor where temperatures as low as 5-10°K are maintained at full operation with a rotor current approaching 250A.

The excitation current is obtained using a brushless type of design where the exciter uses rotating rectifiers to provide power to the mainfield windings. Generally, a small PMG is used on the same shaft to provide the control power.

The major advantage of the wound rotor generator design is the fact that the rotor bound flux can be interrupted without having to separate the rotor from the main engine's shaft. This significantly simplifies the design of all armature protection circuits. This reason explains why the USN/Naval Development Center at Warminster and the Air Force Aero Propulsion Laboratory (Aerospace Power Division), among others, have sponsored work on the wound rotor design for generators.

The clear and major disadvantage of the wound rotor generator is its significantly more complex design due to the presence of field windings on the rotor, which brings with it the requirement for a rather complex cooling system, generally using helium as the cooling medium.

3.3.2 Variable Speed-Drives

Variable Speed-Variable Frequency (VSVF) generators have their rotor shaft directly connected to the engine's shaft which makes for a very compact design. The generator rotor can be connected to either the low speed or the high speed engine shaft. It is more convenient to connect the generator rotor shaft to the high speed engine shaft for two major reasons: the high speed engine shaft only experiences speed variations in a range of 2 to 1 (the low speed range is as high as 4 or 5 to 1); also, it is feasible to use the high speed shaft in a motoring mode to physically start the engine, eliminating the need for any pneumatic or hydraulic starting device.

The nominal rotating speed range is from 5000 RPM to 20000 RPM depending on the operational characteristics of the particular engine where the minimum and maximum speeds vary in a range of 2 or 3 to 1.

In the general discussion primary emphasis will be put on the Permanent Magnet Generator design (PMG) for the VSVF systems. This is done for two major reasons:

- The PMG design presents the more complex version of the regulator problem in order to achieve a constant voltage and constant frequency supply.
- The PMG appears to be the favored design when the generator is to be used as a starter motor as well.

From a strictly generator design requirements point of view there is little difference between variable speed drives and constant speed drives (with the exception of the rotor's dynamic stresses during speed changes for the variable speed drives). The main difference lies in the control systems

required to eventually obtain a constant voltage and constant frequency supply system. For variable speed drives two main philosophies are proposed for the required control circuits:

- Cycloconverter
- dc Link.

In both cases the output of the control circuit should be a balanced three phase, 115/200 V, 400 Hz ac supply. From this supply bus one can then supply the three main potential load categories:

- ac loads, through a direct connection or using step-up or step-down transformers.
- 270 V dc loads, through a direct rectification of the three phase ac supply system.
- 28 V dc loads, through a direct rectification of the three phase ac supply system after it has been reduced by use of step down transformers.

3.3.2.1 Cycloconverter

In the cycloconverter technology the armature windings of the generator are directly connected to the cycloconverter's input (generator mode) terminals. The output of the cycloconverter should then be an ideal 3 phase power source rated 115/200 V and 400 Hz.

The generator armature windings are generally configured for a 9 phase or 6 phase system of voltages. For a PMG these voltages vary with both rotational speed and armature currents. This means that the raw output voltages from the generator windings will vary from high magnitude and high frequency (at low electrical loads and high engine speeds) to low magnitude and low frequency (at high electrical loads and low engine speeds). These armature

voltages are then supplied to the 9 or 6 phase cycloconverter to provide the required constant voltage and constant frequency supply.

The cycloconverter is a static device primarily using Silicon Controlled Rectifiers (SCR). A control circuit compares the generated output voltages, both in magnitude and frequency, with a reference voltage and then computes the appropriate SCR gate control signals to achieve the desired output levels. The SCR's themselves will have relatively high losses (snubber losses) at very high armature voltage levels which is the operating point creating the most severe constraints on the SCRs which generally must be rated 1000 V for a 115/200 V output.

A major advantage of the cycloconverter is that it can be operated in the reverse mode. This opens the road for the use of the PMG as a motor to start the aircraft's engines. In this mode the cycloconverter is connected to an external three phase, 115/200 V, 400 Hz power supply, instead of the airplane's electrical load. The output of the cycloconverter in the motoring mode is a train of pulsed voltages to be supplied to the motor's 9 or 6 phase armature as to create a rotating field thereby creating an electromagnetic torque on the rotor. As is well known, a synchronous machine only develops torque if the stator and rotor fields "travel" at the same speed and if the phase angle difference is kept within acceptable limits. To answer these two conditions, very precise speed and angular position sensors must be mounted on the generator shaft and their outputs must be fed back into the cycloconverter's control circuit. During the initial startup of the motor, the cycloconverter must get its total input power from the external three phase supply and must create extremely slowly rotating fields. As the motor accelerates, the cycloconverter can partially use the armature windings themselves for the required commutation power. This reverse mode of operation for the cyclocon-

verter allows the Permanent Magnet Generator to be used as a starter motor for the engines. This fact alone explains why the cycloconverter, although a rather complex and therefore rather vulnerable device, has received so much attention.

It appears that additional work is required to accurately model the cycloconverter in a dynamic environment (from high speed-low load to low speed-high load) both in its generator and motor modes. A realistic electrical equivalent model should be developed taking into account the engine speed, armature voltage, and load current to derive the output voltage and frequency in the generator mode. Similar models must be developed for the motor mode. Finally, reliability models must be developed for the cycloconverter to simulate its behavior in various degraded modes of operation (one or more SCRs out of service, for example).

3.3.2.1 DC Link

In the dc link technology the armature windings are directly connected to a rectifier. The armature winding arrangement can then incorporate three, six or nine phases but where the three phase configuration is a perfectly acceptable solution. The output of this uncontrolled rectifier is a dc voltage the magnitude of which will vary with engine rotational speed and also somewhat with load current. This dc voltage is then supplied to a controlled inverter the output of which is the desired three phase, 115/200 V, 400 Hz constant voltage-constant frequency supply.

The dc link approach is clearly the simplest of the two techniques being proposed for the variable speed drives to obtain a constant voltage-constant frequency supply. It is also the technique that relies the most heavily on well studied subsystems such as inverters and rectifiers. In view of its

greater simplicity, the dc link may well prove to be the most reliable of the two proposed technologies.

However, the dc link approach cannot be used in a reverse mode operation. Clearly, the dc link itself, i.e. the rectifier-inverter ensemble, can be used in a reverse mode; but, the ac type generator cannot be made to operate as a motor when its armature windings are not supplied with carefully pulsed and coordinated voltages which the dc link cannot do. As a result, the dc link approach appears to be only viable when the generator is not to be used as a starter motor for the aircraft's engines. This would mean that some form of hydraulic and/or pneumatic starter mechanism would be maintained.

Although the dc link is somewhat less complicated than the cycloconverter, accurate equivalent circuits and models must be developed for this device taking engine speed and load current variations into account as well as varying armature voltage magnitudes. Also, for comparative purposes, acceptable reliability models must be developed for the dc link to simulate its behavior in various degraded states.

3.3.3 Constant Speed Drives

The constant speed drive technology uses a configuration where the generator rotor is directly attached to the output of a variable speed converter, generally called Constant Speed Drive (CSD), which transforms the variable engine speed (4700 RPM to 8850 RPM in the case of the Boeing 747 E4B) to a constant rotational speed such as 12000 RPM for a 4 pole 400 Hz machine. The CSD is a hydraulical speed converter using special MIL-L-23699 oil as the working fluid. A key concern here clearly is the proper cooling of the working fluid. The CSD itself is attached to the engine shaft through a Quick

Attack Detach (QAD) mechanism to protect the drive in case of any catastrophic failures.

From a control systems point of view the constant speed drive is rather simple in that no frequency transformation or adjustment is required as the frequency of the generator armature voltages is maintained constant by the drive itself. However, some voltage adjustment and control circuit is required specifically if a Permanent Magnet Generator is used. This voltage adjustment circuitry is very standard in that it uses classical voltage control techniques with various feedback loops and a set reference voltage.

Constant speed drives have two rather fundamental disadvantages as follows:

- a. As mentioned earlier, they do require bulkier nacelles which means a higher drag coefficient for the aircraft.
- b. They cannot be used in a reverse mode operation to start the aircraft engines. Indeed, the CSD is not a reversible type of drive as it uses hydraulics rather than standard gears. Also, the constant voltage controller is not capable of creating the set of pulsed armature voltages required to get the ac machine to create electromagnetic torque.

It is believed that the constant speed drives are only a viable alternative when nacelle drag is not a factor and when no starting operating mode is required. If these two requirements are met, then the CSD could be an interesting option in view of its less complex control circuits.

3.3.4 Two Examples of Modern Generators

3.3.4.1 Permanent Magnet Generator

The General Electric Corporation has participated, as the prime contractor, in the development of a PMG with the following characteristics:

Continuous rating: 210 KVA @ 155 V

Operating speed: 12000 to 21000 RPM, max 23100 RPM

Maximum power: 344 KVA @ 145 V

Minimum starting torque: 258 Nm (190 ft.lb.)

Corresponding to the requirements of a 40000 to 55000 pound thrust engine.

Rotor:

- Permanent magnet: Samarium Cobalt
- 14 poles
- 16.51 cm diameter
- 17.78 cm length
- uses a so-called "shrink ring" to hold a total of 98 magnets in place. The shrink ring is the key mechanical component of the generator from a stress point of view. The shrink ring thickness is 0.64 cm for a stress level of 155000 PSI.

Stator:

- Inside diameter: 16.79 cm
- Outside diameter: 19.36 cm
- Length: 17.78 cm
- 63 slots, 14 poles, 9 phases

Weight: approximately 0.1 lb/KVA

3.3.4.2 Wound Rotor Generator

The Westinghouse Electric Corporation has participated, as the prime contractor, in the development of a wound rotor generator with the following characteristics:

Continuous power rating: 10 MVA @ 5000 V

Rotor:

- 4 pole wound rotor, helium cooled
- 12000 RPM
- Outer diameter: 24.89 cm
- Length: 71.73 cm
- Rotor current: 230 A (5 MVA case)
- Field energy: 30 KJ
- Helium consumption: 30 l/hr
- Temperature: 5-15°K

Stator: 3 phase winding design.

Weight: approximately 0.1 lb/KVA.

3.4 Actuators

3.4.1 Basic Issues

All-electric actuators are expected to take the place of hydraulic actuators for both flight control surface actuation and landing gear deployment and retraction. Both of these loads require very high torques to be supplied for rather short durations and at very slow rates for electrical machines. A fundamental choice exists between the utilization of rotating or linear machines. The present choice overwhelmingly favors the rotating machine implementation for actuators. The rotating motor implementation offers very

interesting possibilities from a space occupation point of view when using the "hinge mounting" technique where the actuator is directly mounted in the hinge between the flying surface and the control surface.

As the flight requirements call for a high torque low rate type of power and as electrical motors are more conveniently designed for a lower torque and higher rates, a sophisticated gear box mechanism must be used between the electrical motor and the flight control surface to be actuated. Typically, a rotating electrical actuator will develop speeds of up to 9000 RPM. The computation of the optimal gear ratio to be used for any given actuator situation is a non-trivial task but, which is not addressed in this report as the optimal gear ratio will be assumed to be known for any electrical distribution system study.

As a direct result of the rather high rotational speeds reached by these actuators, and in view of the very short times to reach these high rotational speeds and to come back to zero, it is imperative that the rotors have very low moments of inertia. This requirement can only be met if the rotor has a very small diameter. To achieve the desired minimum electromechanical torque, which remains substantial in spite of the gear box, the length of the rotor will have to be significant since the electromechanical torque is proportional to the volume of the rotor. Fortunately, this thin and long design of the actuator rotor is fully compatible with the hinge mounting requirement.

The most commonly proposed and used electrical rotating actuators are of the dc brushless type. This is really a misleading nomenclature from an electrical machines point of view. In reality, a standard ac synchronous machine design is used with the armature windings (generally three phase) located in the stator and the flux source located on the rotor. The brushless nomenclature refers to the fact that a permanent magnet is used as the flux

source. In most cases Samarium Cobalt rotors are used. As the ac synchronous machine with an Sm Co rotor has already been discussed in paragraph 3.3, no further descriptions are required here.

The armature windings are controlled using a rather standard commutator control circuit which provides the stator with a set of pulsating voltages simulating a rotating stator field, the speed of which is adjustable. The commutator circuit can be based either on SCRs or on power transistors. The commutator circuit is supplied from a dc voltage source generally rated at 270 V dc rather than 28 V dc in view of the currents required by these actuators. Two types of commutators can be designed.

- Providing for regenerative braking where the motor is slowed down by using it as a generator to provide energy back into the power source. Although this is not a major complication of the control circuit, it is of no practical use unless some kind of auxilliary or primary battery is available on board and is connected in parallel with the primary power source. This type of control circuit is used on board of the Space Shuttle in conjunction with its elevon actuator.
- Not providing for regenerative braking which is used in most cases.

Although the commutator control circuits are well known, one must implement accurate electrical equivalent circuits for them to be used in overall distribution system analysis programs. These models need not get involved with the device's internal structure, only the input-output characteristics are of interest.

Several types of direct drive rotational actuators must be distinguished as follows:

- Reversible, which are generally of the high efficiency type.

- Irreversible which can again be sub-classified into:
 - High efficiency gear trains which use mechanical no-back or brake devices to hold position of the control surfaces;
 - Low efficiency gear trains which rely on mechanical configuration and losses to hold position of the control surfaces.

For reliability reasons most hinge mounted actuators are generally mounted in pairs where the entire load can be sustained by only one actuator. The two hinge mounted actuators are then mounted together by use of some differential device, generally a planetary differential device.

To provide for accurate reliability studies, the equivalent models of the electrical actuators must be able to depict situations where both actuators share the load through the differential and when only one actuator picks up the entire load. One must also determine some reliability figures for the differential device itself.

In many cases where regenerative braking is not used, an electromagnetic brake assembly is used on each actuator.

The behavior of the electromagnetic brake device may have to be modeled in view of the significant in-rush currents it could require.

3.4.2 Some Examples of Installed Electrical Actuators

All modern electrical actuators referred to in the literature are of the dc brushless type described earlier in this paragraph. The alternate technology would be an ac induction motor being supplied from a variable frequency-variable voltage source. However, the dc brushless machine provides an almost two fold greater duty cycle capability when compared to the ac machine of the same physical size. This is primarily due to the fact that in the dc machine all heat losses occur in the stator where they are relatively easy to evacuate.

3.4.2.1 The Space Shuttle Elevon Actuator

This actuator was developed by the DELCO Electronics Division of the General Motors Corporation. It is rated 17 Hp and is supplied from a high voltage battery. As a result of the battery source, regenerative braking is used.

The actuator has an 8 pole permanent magnet rotor rated at 9000 RPM with maximum test speeds of 30000 RPM. The stator is a three phase armature winding which is liquid cooled and which uses a nonmetallic sleeve to contain the coolant in the stator portion of the motor.

The characteristic dimensions of the actuator are:

length: 11.25 inches

weight: 17.16 pounds.

3.4.2.2 AiResearch Manufacturing Dual Actuators

AiResearch has proposed a dual actuator assembly supplied at 270 V dc. The maximum current is 34 A total for both motors.

The maximum torque is 37500 pound inches.

The output rate is 80 degrees/second.

The frequency response is 8 Hz.

The assembly uses two electromagnetic brake devices.

3.5 Miscellaneous Topics

3.5.1 Existing Load Modeling

As mentioned earlier, in paragraph 3.2, emphasis should be placed on the determination of the exact types of power supplies which are feasible for each type of avionics and instrumentation loads. In addition, one must carefully establish how these various loads react to both voltage and/or frequency variations for ac supplies and voltage variations for dc supplies. This work has most certainly been already done and only a review and compilation of existing data is required to establish the data base needed for the electric distribution analysis package.

3.5.2 Distribution Cable Technology

Little mention is made in the available literature of the cable technology which is to be used in conjunction with an all electric aircraft (AEA). The key issues here are the current ratings which are acceptable for an AEA application in regard to acceptable heat dissipations. Another major concern is that not all available cable insulation materials are acceptable on board of aircrafts in view of their fire resistance properties. Finally, several cable designs now in use may not be suitable for higher power levels at high frequency such as 400 Hz. It may be necessary to develop alternate equivalent circuits for distribution cables operating at high power transfer levels and at 400 Hz.

3.5.3 High Power Airborne Transformers

The power capabilities of transformers are limited by the rate at which the internally generated heat can be removed. The feasibility of developing continuous duty lightweight high power airborne transformers having a specific weight of 0.25 lb per KVA of 400 Hz has been successfully established. Most techniques of transformer design use an approach based on slight variations in the ideal transformer to represent the actual device under consideration:

- Nearly infinite permeability core.
- Negligible interwinding capacitances.
- 100% flux linkage between windings.
- Negligible core loss.
- Negligible winding loss.

Two approaches to transformer design have been developed: The first approach has been called the steady state analysis routine; it is a magnetic circuit approach which uses flux and flux linkage concepts to relate the primary and secondary sides of the transformer. The second approach has been called the real time analysis routine; it is a coupled electric circuit approach in which the primary and the secondary sides are related through their inductance.

Freon was selected to be the coolant for the transformers; because of its low cost, suitable thermodynamic and electrical characteristics, availability, and ease of handling (non-flammable and non-toxic).

Available Transformer Technology

50 KVA Transformer

208 volt 3 phase/10 KV 3 phase

frequency 400 Hz, designed for continuous duty

total weight: 21 pounds, 0.42 lb/KVA

dimensions: 4 x 8 x 10 in; 6.4 in³/KW

efficient = 90% (at rated load)

High frequency inverter type transformer (utilizing pie winding)

200 KW, 25 KV secondary

efficiency = 96%

specific weight 0.14 lb/KW

A program is underway for the development of lightweight pulse transformer technology with secondary voltages from 50 to 250 KV, and pulse energies from 10 to 100 KJ.

Inverter transformer designs at higher power show projected specific weights as low as 0.01 lb/KW.

It is of interest to note that for the past five years, transformer technology has not been discussed or developed in papers regarding power systems in an all electric aircraft; which means that the latest developments were successful as far as, rated power, weight, volume, efficiency, and reliability.

4. SYSTEM EVALUATION AND ANALYSIS

4.1 Statement of Objectives

The decision issues associated with the aircraft power system fall into two broad categories: (1) Design, and (2) Operations.

The key design objectives are those of a (a) reliability, (b) high quality of delivered power, (c) minimum weight, and (d) reduced costs. Obviously, these objectives are related to one another. For example, higher system reliability will imply, in many instances, the introduction of various levels of redundancy; thus increasing both weight and cost. A reasonable procedure to follow here is to fix both reliability and power quality standards, and then optimize system design for reduced weight and cost.

A key issue associated with the above design questions, consists of the availability of adequate data, on cost and reliability, especially when it comes to new technologies with short performance records. Thus any proposed methodology dealing with this problem should contain elements which will factor in data uncertainties in manners which can help the decision-maker in assessing the risks involved.

Operational objectives pertain to evaluating system performance over the range of credible missions the aircraft is supposed to undertake. This poses questions of system operations under various types of contingencies. A highly reliable design may have a serious weakness in certain contingencies thus lowering the survivability of the aircraft. Invariably, because of the dynamic environment of system operations, the role of control emerges as an important factor. Not only is it needed for equipment protection, but also to maximize aircraft effectiveness under various conditions. Smart load management inevitably is the logical answer. Criteria for assessing these control functions should be clear and concise.

The developed methodology, as a result, focuses on the following

objectives:

- a. Development of computational analysis procedures to evaluate the design issues of reliability, quality of delivered power, weight and costs.
- b. Development of guidelines for the decision-maker to assess the above design issues given various levels of data uncertainties.
- c. Development of procedures to evaluate system operations, incorporating the role of smart load management, from the point of view of maximizing power delivery to key components.

4.2 Methodological Structure

Functionally, power flows from generators to the load via the transmission network. The load with its requirements (power levels, voltage, ac vs. dc, location, priority, and timing use) constitutes the driving force which dictates the selection of transmission/distribution and generation systems (see Figure 1).

Effectively, load system specifications define the first set of options. For the AEA incorporation of electric actuators and elimination of bleed air requirements pose major changes in load requirements for design and operational purposes (see Chapter 3). For a given design these specifications are fixed. Consequently, alternative transmission/distribution and generation systems are defined for delivery of power to those loads. The options here consist of the following:

- Transmission and distribution system
- Generation System
- Control System.

These options are defined initially on the basis of established power engineering principles (see table 4.1). Note, for example, that the selection

of a particular generating system will impose serious restrictions on the type of power delivered (ac vs. dc, as well as, voltage levels). The attempt is made to enlarge the set of options in order to provide an understanding of the tradeoffs involved. An important distribution design question, for example, involves the use of transformers with many pieces of equipment. The tradeoff involves the substitution of many transformers by a fewer number plus additional wiring, for example. An overall option, therefore, corresponds to a complete configuration of generation, transmission, distribution and load systems.

For every configuration the analysis covers the following issues:

- a. Reliability and risk analysis
- b. Operational performance analysis
- c. Sensitivity analysis.

These will be discussed in the next section. Figure 2. below outlines the logical flow of the structure of the methodology. Table 4.2 defines the technical developmental issues involved.

4.3 Analysis Procedures

4.3.1 Reliability and Risk Analysis

The reliability issue originates with information on component failure rates and repair times and ends up with measures of load supply (or interruption) probabilities to various system loads. Since interest is in the power system itself, the failure of a load component is not a power system issue, per se, although it is an important one for the designer. The methodology, however, can be extended to include load device failures, in which case the reliability issue becomes part of a broader context of overall system

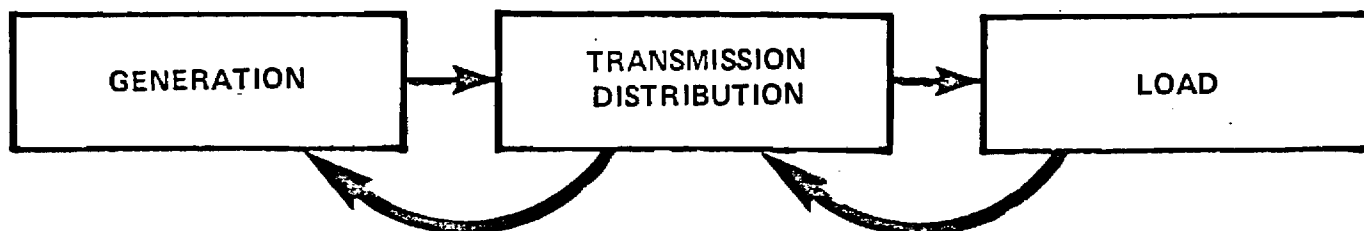


Figure 1. Key System Blocks and Their Interrelationships.

TABLE 4.1: PARTIAL LIST OF DESIGN OPTIONS

Category	Options
1. Transmission and distribution system	1.1 Network configurations (a) radial (b) meshed or looped 1.2 Voltage (a) All ac (b) All dc (c) Hybrid 1.3 Transformer allocation
2. Generation system/engine configuration	2.1 Four engines, two on each wing 2.2 Two engines, one on each wing 2.3 Three engines, one on each wing one in the tail 2.4 Three engines, all three in the tail 2.5 Two engines, all in the tail
3. Generation system/technological	3.1 Variable speed drives (a) PMG/Cycloconverter (b) PMG/dc link 3.2 Constant speed drives
4. Control system	4.1 Relay coordination/breaker action 4.2 Load management 4.3 Preventive control 4.4 Corrective control

**TABLE 4.2: ANALYTICAL ISSUES ASSOCIATED
WITH EVALUATION PROCESS**

Subject	Issues
Reliability and risk	(a) Required development of a meshed network analysis reliability analysis program (b) Incorporation of load component reliability
Generator Systems	Development of steady-state and possibly transient models for new technology
Power Flow/Voltage Profile	(a) Adaptation of available models on 3-phase and multiphase ac analysis (b) Modeling of ac/dc links including inverters (c) Separate algorithms for radial and meshed networks
Short Circuit Analysis	(a) Incorporation of 3-phase and multiphase analysis (b) Modeling of ac/dc links
Operational Performance Analysis	(a) Contingency analysis software development in association with above power flow models. (b) Preventive and corrective control strategy models
Load Models	Actuators, avionics, etc. electrical steady state and transient models.

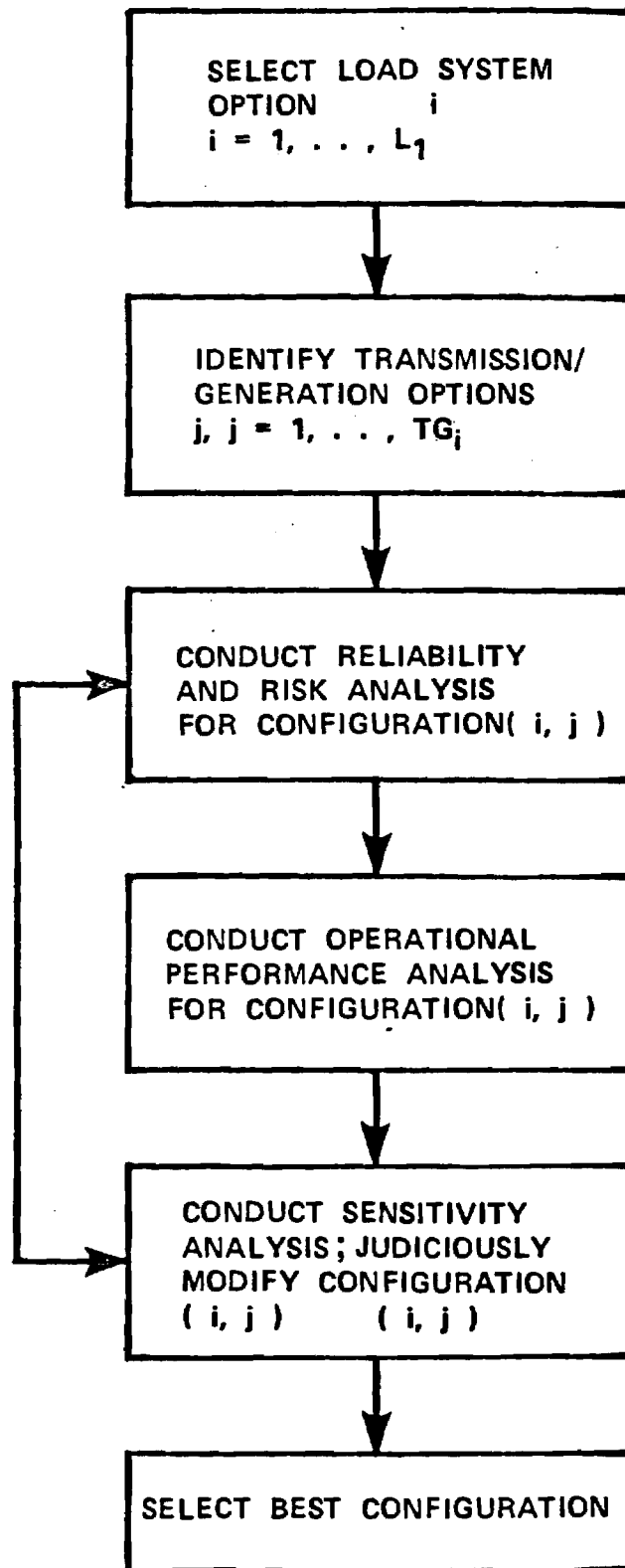


Figure 2. Simplified Logic Of Overall Methodology.

reliability. This latter situation, for example, can be adopted to draw reliability comparisons between conventional (hydraulic) and all-electric actuation systems.

The literature on reliability analysis of power systems is quite abundant (see [A15 - A18]). Most approaches originate with a basic concept on component failure rates (the bath-tub model; see Fig. 3.), and the component Markovian state model (Fig. 4.). When components are connected in series or in parallel, approximate 2-state models can be constructed. This has been found quite adequate for distribution system reliability [A15]. For simple distribution systems like those of the aircraft power system, the probability of failing to supply load to a given power can be evaluated directly. Network concepts of cut sets, have been employed in this regard [A16] and we feel can be accommodated to the problem at hand.

Consequently, for a particular configuration, the reliability of supply to every load in the network can be evaluated. Furthermore, given the load-device reliability, the functional reliability of that device can be computed.

Overall system reliability will depend very much on the load management logic (or priority system employed). For a given priority system, the above information can be integrated into a small vector of reliabilities associated with the priority functions of the aircraft. A scalar reliability measure can be formed as a weighted sum of the components of the functional reliability vector. The scalar measure may be of value in comparing alternative configurations, but should be interpreted with extreme caution. Figure 5. provides a simplified block diagram for the reliability evaluation process.

Given reliability values for a specific configuration (i,j), the next step is to carry out sensitivity analyses in order to identify the potential(s) of given improvement(s). These sensitivities are obtainable through

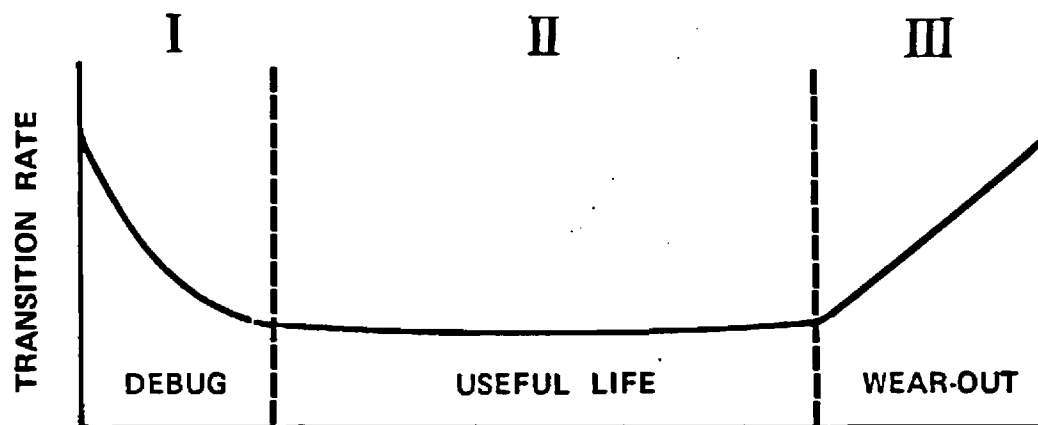


Figure Typical Bath-Tub Curve For Component Failures.

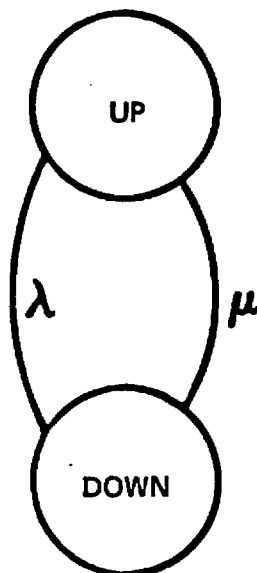


Figure 3. Markovian State Model For A 2-State Component
(λ = Failure Rate, μ = Repair Rate)

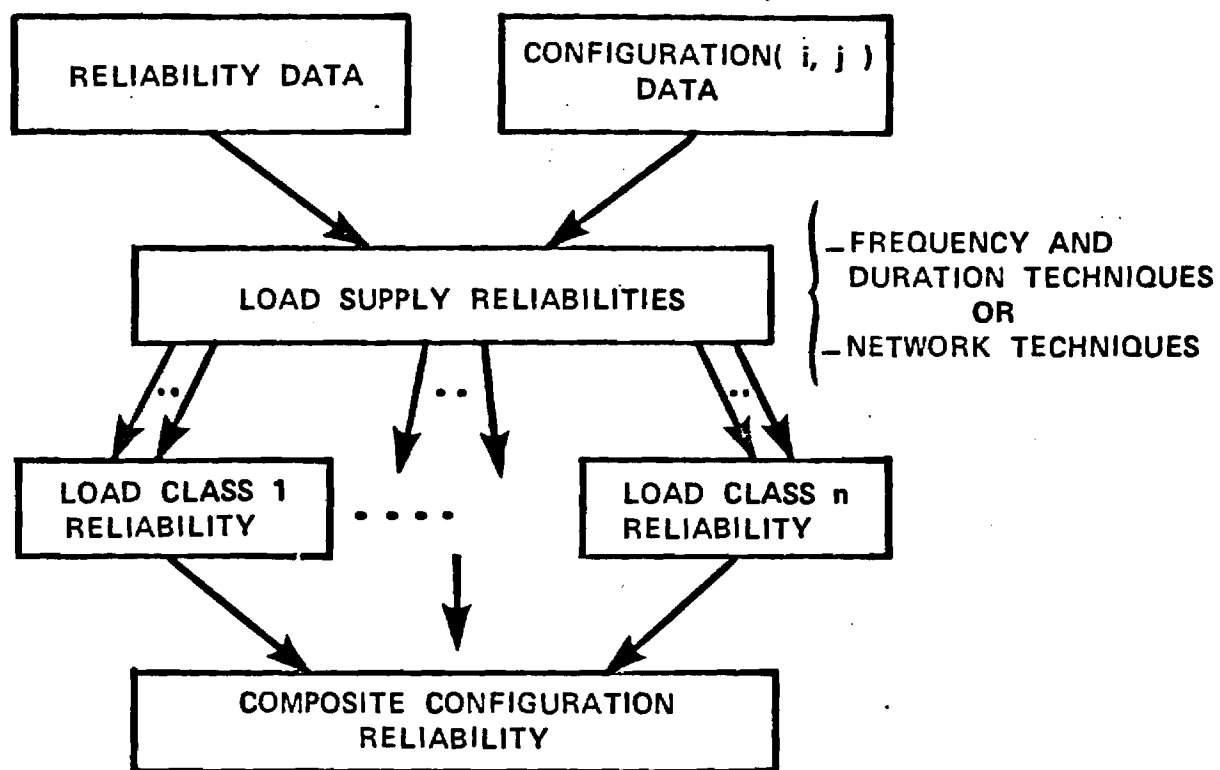


Figure 4. Simplified Structure For Reliability Evaluation.

variations in the input reliability data, or some credible variations in the configuration under study. Not only will the decision maker obtain reliability information on the given configuration, but also on the possible improvements on that configuration within a credible range of input data variations and/or design modifications.

In many aspects, the above sensitivity analysis will help the decision maker in assessing the risks involved by choosing a particular configuration. Thus, if the uncertainties associated with a given technology are well understood, then a possible risk measure will be the expected unreliability over the probability distribution of these uncertainties. In effect, this will reduce sensitivity analysis into a small number of merit figures, which can then be used in the overall assessment.

4.3.2 Operational Performance Analysis

The issues involved here pertain to the quality and availability of power supplies to the loads during aircraft missions under normal and contingent operational conditions [A14].

Quality of power supply to given load corresponds to the ability of the power system to continuously provide the power within the load power requirement specifications. These are translated into specification on voltage levels, system frequency (for frequency-sensitive ac loads), and transient effects.

Availability of power supply is dependent on expected contingencies during specific missions. The contingencies themselves are functions of the aircraft type, the mission itself, and past experience. Credible contingencies will correspond to single, double, and possibly, multiple mode failures.

The working tools to assess both quality and power supply availability consist of quasi steady-state network and component models of the system.

Specifically, we require two types of models:

- a. Voltage profile model
- b. Short circuit model.

For the system(s) at hand both models pose serious and challenging technical developments. The envisioned voltage profile model will require developments in the following areas (see table 4.2):

1. Proper modeling of different types of generating units.
2. Proper modeling of the various types of load.
3. Proper modeling of the transmission/distribution network based on a 3 phase ac linked to a dc portion with proper representation of converters.

Similar developments are envisioned with the short circuit portion of the model.

Of particular importance will be the incorporation of load management control logic in both models, together with the protective relay coordination scheme. The study will have to delve into the "what-if" questions conceivably poor voltage profiles, or poor relay coordination under might result under certain contingencies, for what might otherwise seem to be a reliable configuration.

A typical performance evaluation analysis run for configuration (i,j) will consist of the following steps:

1. Normal Mission profile: For a normal mission configuration (start-up, taxiing, take-off, cruising, landing, taxiing, and shut-down) establish voltage profiles for all loads, by means of 3 phase ac/dc load flow program to be developed. The analysis will show outputs at functions of time using quasi-steady state models.
2. Contingency Analysis: Analyze voltage profiles, and system

protection performance for specified contingencies during mission, using both load flow and short circuit programs, as well as, proper representations of load management controls and the protection system.

In analyzing the results, the relationships among contingencies and corresponding performance degradations will be delineated for the final assessment by the decision maker. In so doing it will be quite conceivable to define logics for pre-contingency preventive actions, as well as, post-contingency corrective actions.

4.4 Data Requirements

Table 4.3 defines a typical set of equipment data requirements. The emphasis here is on electrical, reliability and operating limit data, together with weight (and possibly volume) data. Since cost data may be variable due to future uncertainties, it will not be required. However, the analysis program will be able to evaluate absolute or relative system costs, based on information provided by the user.

Other pieces of data will consist of (a) Base case networks, (b) Base case mission scenarios, and (c) Credible mission contingency lists.

At present, the C5A base case network configuration is available and can be used as a starting point. Available also are some typical mission scenarios which describe electrical loadings at various mission stages. These can also be used for initial analysis. Mission contingencies, however, should be defined by the user in order to minimize the computational effort and/or avoid unrealistic contingencies.

TABLE 4.3 EQUIPMENT DATA REQUIREMENTS

Equipment Type	Data Requirements
Generators	type, model, rating,
AC/DC Transformers	electrical characteristics,
AC/D Converters	electrical model parameters,
Cables/Wires	weight, failure rate, expected repair time, cost range (if available), operating limit specifications.
Relays	Typical relay characteristics, relay type.
SSPC Controllers	Functional descriptions; expected failure rates; power requirements.
Loads	Individual load class definitions, power requirements, operating voltages and currents, operating limit specifications, major component failure rates, weight.

4.5 Discussion and Conclusion

The main thrust of system evaluation and analysis is to develop those analysis tools which will help the decision maker, as well as, the designer, in selecting both reliable and operationally robust designs for the aircraft power system, taking into account such important factors as weight and volume.

The key decision options relate to the selection of compatible combinations of generation, transmission/distribution, ac/dc interfaces, smart control and protection, in order to maximize reliability and operational performance.

Although reliability analysis is based on classical power system approaches, some innovations are required in the network reliability portions, the proper selection of reliability indices, and in the incorporation of load priority logics in the analysis. By extending reliability information to the load components themselves, the analysis is adapted to analyze higher level issues of overall system reliability.

Operational performance analysis is necessary in the evaluation of system robustness against credible contingencies. Technically, this will require key innovations in the component modeling of new generation system technologies, 3-phase ac and ac/dc interfaces for both voltage profile (load flow) and short circuit analysis.

5. CONCLUSIONS

The main conclusions of this study are:

- (1) Electric power supply and distribution will become increasingly critical to the functional operation of future aircraft.
- (2) New and developing technologies will have considerable impact on power system requirements.
- (3) Existing power supply and distribution systems will not provide sufficient reliability and operational flexibility.
- (4) Significant opportunities exist to enable substantial improvements in aircraft design and performance by appropriate design of the electric power system.
- (5) Analytical procedures, representing adaptation and augmentation of those applied to the electric utility system, can be extremely useful in aircraft electric power system design and evaluation.
- (6) Successful implementation of analytical procedures for the design of aircraft electric power systems will require an extensive effort to develop appropriate models for specialized aircraft electric apparatus and loads.

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